# Mechanical Properties of Paddy Grains under Quasi-Static Compressive Loading

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**Abstract:** Knowledge of the mechanical properties of paddy grains is important in the analysis and prediction of their cracking and/or breaking behavior during handling and processing. In the current study, fracture resistance of paddy grains was measured in terms of average grain rupture force and energy absorbed under quasi-static compressive loading condition. Two paddy varieties, Alikazemi and Hashemi, were quasi-statically loaded in horizontal and vertical orientations at two loading rates of 5 and 10 mm/min. In this research 8 treatments were performed as randomized complete block design with 10 replications for each treatment. In the case of Alikazemi variety, as the loading rate increased from 5 to 10 mm/min, the force required for initiating the grains rupture decreased from 125.69 to 117.38 N and 33.51 to 29.94 N, and the energy absorbed at the grains rupture decreased from 42.70 to 36.80 mJ and 30.85 to 24.59 mJ, respectively, at horizontal and vertical orientations. For the Hashemi variety, the grains rupture force decreased from 109.96 to 88.33 N and 25.39 to 21.68 N, and the grains rupture energy decreased from 34.39 to 29.23 mJ and 26.98 to 21.27 mJ, respectively, at horizontal and vertical orientations with an increase in loading rate from 5 to 10 mm/min. The values of rupture force and rupture energy of paddy grains for Alikazemi variety were higher than those of the Hashemi variety. [New York Science Journal 2010;3(7):40-46]. (ISSN: 1554-0200).

**Keywords:** Mechanical properties; Paddy; Rupture Force; Energy; Variety

## 1. Introduction

Rice *(Oryza Sativa* L.*)* is an ancient and important cereal grain crop in the world that has been used for serving the staple food of world's population since past times. World rice production has increased from 520 million tonnes in 1990 to 658 million tonnes in 2007 (FAOSTAT, 2007). In Iran, rice is widely cultivated on an area of about 615000 ha with an annual production of about 3.0 million tonnes. Main areas of rice cultivation in Iran are located in Mazandaran and Guilan provinces producing 75 percent of Iran's rice crop. In Guilan province, the most popular varieties grown are local and aromatic varieties such as Hashemi and Binam (Alizadeh et al., 2006).

During various stages of rice processing, from harvesting to final production, the performance intensity of the used equipments may lead to create fissures in the grains and consequently result in the grains breakage during de-husking, milling and other subsequent projects. Contrary to other cereals, rice is preferably consumed as whole grains. An important quality criterion for the rice industry is therefore the percentage of whole and unbroken rice kernels. The economic value of the dried product is strongly dependent on the percentage of unbroken kernels (Siebenmorgen, 1994). So, in order to accurate design of the handling and milling machinery to minimize the grains damage, information on such engineering properties of paddy grains as force and deformation curve must be provided.

Recently, rheological properties of several grains have been reported in the literature. The stress, strain, modulus of deformability and energy to yield point were found to be a function of loading rate and moisture content for different varieties of wheat kernels (Kang et al., 1995). The maximum compressive stress for wheat and canola decreased linearly with an increase in moisture content (Bargale et al., 1995). In a study, Isik and Unal (2007) observed that the shelling resistance of white speckled red kidney bean grain decreased as the moisture content increased from 98.26 to 53.67 N. Lately, a similar study was done by Altuntas and Karadag (2006) that the mechanical properties of sainfoin, grasspea, and bitter vetch seeds were determined in terms of average rupture force, specific deformation and rupture energy. The mean values of rupture force, specific deformation and rupture energy for sainfoin seed were 7.40, 9.72 and 4.56 N; 8.94 %, 1.71 % and 9.97 % and 1.97, 0.46 and 0.71 N mm for along X-, Y- and Z-axes, respectively. The mean values of rupture force, specific deformation and rupture energy for grasspea seed were 254.40, 42.60 and 100.80 N; 27.53 %, 0.29 % and 14.03 %; and 187.20, 29.25 and 38.77 N mm for along X-, Y- and Z-axes, respectively. The mean values of rupture force, specific deformation and rupture energy for bitter vetch seed were 57.60, 45.00, 87.00 N; 7.60 %, 1.62 %, 1.93 %; 10.14, 4.42, 0.86 N mm for along X-, Y- and Z-axes, respectively. Kunze and Choudhury (1972) determined the tensile strength of moisture-absorbing individual rice kernels of the Bluebelle and Nato varieties. After equilibration at 44 % RH and 23.3 ˚C the rice grains were exposed to an environment of 100 % RH at the same temperature and the tensile strength measured at regular time intervals. The observed tensile strength ranged from 14.3 MPa at initial equilibrium (44 % RH) to 3.14 MPa after 40 min exposure time. Prasad and Gupta (1973) subjected flat-positioned paddy grains of the IR-8, Padma and Patnai-23 varieties to lateral compression loading at deformation rates ranging from 0.5 to 10 mm/min at moisture contents of 12, 15, 18, 21 and 24 % (d.b.). They observed a greater change in yield point values between 12 and 18 % (d.b.) moisture content than in the range 18 to 24 % (d.b.). The rice was found to behave more 'fluidlike' at higher moisture content levels. Chattopadhyay et al. (1978) determined the dynamic stiffness of brown rice, variety IR-8, using cylindrically-shaped specimens tested uniaxially along the cylindrical axis. Elastic modulus and loss modulus were determined at forcing frequencies from 100 Hz to 1000 Hz and at four different moisture contents, 12, 17, 22 and 29 % (d.b.). It was found that the elastic modulus decreased with increasing moisture content, ranging from 3705 MPa at 12 % (d.b.) to 669 MPa at 29 % (d.b.). It was recognized that, for engineering purposes, failure stress levels should also be determined in addition to stiffness. Chattopadhyay et al. (1981) carried out two types of uniaxial compression loading (constant displacement rate and sinusoidally varying stress) on brown rice, variety IR-8, to determine its rheological behavior over a widely-varying time period. They found that with a time decrease from 120 s to 0.00016 s the viscoelastic relaxation modulus increased 15, 25, 16 and 20 fold at moisture contents of 12, 17, 22 and 27 % (d.b.), respectively. The results also showed the great influence of moisture content on the mechanical properties of the high starch grain.

The objective of this research was to determine fracture resistance of two different varieties of paddy grains by examining the effect of variety, loading rate and grain orientation on rupture force and energy of the grain.

**2. Material and Methods**

The paddy varieties, Alikazemi and Hashemi, used for this study was obtained from the Rice Research Institute, Rasht, Iran. The varieties used in the current study were two popular rice varieties in north of Iran that characterized by long kernels having long own (Fig. 1). The initial moisture content of the samples was determined by oven drying method at 103 ˚C for 48 h (Zareiforoush et al., 2009). The initial moisture contents of grains were 14.6 and 14.8 % (w.b.) for Alikazemi and Hashemi varieties, respectively. In order to create an equal level of moisture content, 14 % (w.b.), the samples were kept in an oven at a constant temperature of 43 ˚C until the desired moisture content of the samples was obtained (Yang et al., 2003; Zareiforoush et al., 2009).

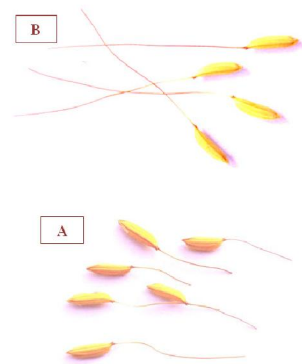


Figure 1. Paddy varieties, A: Alikazemi variety; B: Hashemi variety

The mechanical properties of paddy grain were determined in terms of average rupture force and energy at horizontal and vertical orientations (Fig. 2) for two different varieties of Alikazemi and Hashemi. The experiments were also conducted at two loading rates of 5 and 10 mm/min. Quasi-static compression experiments were performed using a proprietary tension/compression testing machine (Instron Universal Testing Machine /SMT-5, SANTAM Company, Tehran, Iran).

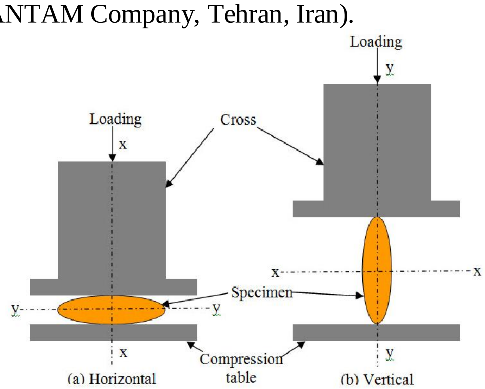


Figure 2. Orientations of paddy grain under compressive loading

For each treatment ten grains were randomly selected and the average values of all the 10 tests were reported. The individual grain was loaded between two parallel plates of the machine and compressed at the preset condition until rupture occurred as is denoted by a bio-yield point in the force–deformation curve. The bio-yield point was detected by a break in the force–deformation curve. Once the bio-yield was detected, the loading was stopped. In order to determine the effect of the orientation of grain against loading, the grain was positioned horizontally (Fig. 2a), with the major axis of the grain being normal to the direction of loading, or lengthwise. For vertical loading (Fig. 2b), the major axis of the grain was parallel to the direction of loading. The deformation (strain) was taken as the change in the original dimension of the grain. Note that load cell deflection under load was found to be negligible for loads used in this study. The energy required for causing rupture (failure) in the grain was determined by calculating the area under the force–deformation curve up to grain rupture. The latter procedure was done by the utilization of computing software installed on the apparatus used.

This study was planned as a completely randomized block design. Experimental data were analysed using analysis of variance (ANOVA) and the means were separated at the 5% probability level applying Duncan's multiple range tests in SPSS 15 software.

## 3. Results and discussion

Table 1 shows the individual effects of variety, loading rate and grain orientation on rupture force and energy of the paddy grains. Analysis of variance of data indicated that the grain variety and grain orientation significantly ($P$ < 0.01) affected rupture force and energy. The effect of loading rate on the rupture force and rupture energy of paddy grains was significant at the 5% and 1% levels of probability, respectively. Based on the statistical analysis, the interaction effect of grain orientation × loading rate on the rupture force and rupture energy was significant at the 5% and 1% probability levels, respectively. The interaction effect of grain variety × loading rate on the grains rupture energy was significant at the 5% probability level; while the effect on the value of grains rupture force was not significant. Finally, the interaction effects of grain variety × grain orientation and grain variety × loading rate × grain orientation on the grains rupture force and energy was not significant ($P$ > 0.05).

In the case of Hashemi variety, the average force to rupture the grain was obtained as 61.34 N varying from 21.68 to 109.96 N, while for Alikazemi variety, the required force to rupture the grain varied from 29.94 to 125.69 N with the average of 76.63 N (Table 2). The average rupture energy of the Hashemi variety was acquired as 27.97 mJ ranging from 21.27 to 34.39 mJ, whereas for Alikazemi variety, the energy absorbed until the grain rupture varied from 24.59 to 42.70 mJ with the average of 33.74 mJ.

Table 1. Individual effects of variety, loading rate and grain orientation on paddy grain rupture force and energy

| Variety | Rupture force (N) | Rupture energy (mJ) |
|---|---|---|
| Alikazemi | 76.628 a* | 33.736 a |
| Hashemi | 61.341 b | 27.969 b |
| Loading rate (mm /min) | | |
| 5 | 73.637 a | 33.731 a |
| 10 | 64.332 b | 27.975 b |
| Grain orientation | | |
| Horizontal | 110.339 a | 35.781 a |
| Vertical | 27.631 b | 25.924 b |

*The means with the same letter are not significantly different according to Duncan's multiple ranges test.

In the following paragraphs, the effects of each factor on the rupture force and energy are comprehensively discussed.

### 3.1. Rupture Force

The mean comparison of rupture force of paddy grains at different varieties, grain orientations and loading rates is shown in Table 2. As it can be seen, the required force to initiate the grains rupture in the case of Alikazemi variety was higher than that of the Hashemi variety, at similar conditions of the grains orientation and loading rate. The results also revealed that the value of grains rupture force at horizontal orientation was higher than that of vertical orientation, for both the Alikazemi and Hashemi varieties. This is possibly due to the lower surface of the grains provided versus the loading plate at vertical orientation. Gupta and Das (2000) evaluated the fracture resistance of both sunflower seed (*Helianthus annuus* L.) and its kernel in terms of average compressive force, deformation and energy absorbed per unit volume at rupture. Their results indicated that as the direction of loading changes from horizontal to vertical position, the average compressive forces required to cause kernel rupture significantly decreases from 33.94 to 26.86 N. In the case of the seed hull, the trend was the opposite. Poulsen (1978) examined the fracture resistance of soybeans under compressive loading. He measured the average compressive force, deformation and toughness under quasi-static loading conditions when the hilum was in both horizontal and vertical positions. The seed developed seed coat cracks at lower levels of force when it was loaded with the hilum in the vertical position than when it was loaded with the hilum horizontal.

Table 2. Mean comparison of rupture force of paddy grain at different varieties, grain orientations and loading rates

| Grain Orientation | Rupture force (N) Horizontal | | Rupture force (N) Vertical | |
|---|---|---|---|---|
| Variety | Loading rate | | | |
| | 5 mm/min | 10 mm/min | 5 mm/min | 10 mm/min |
| Alikazemi | 125.69 (22.54)* | 117.38 (6.67) | 33.51 (6.24) | 29.94 (2.04) |
| Hashemi | 109.96 (17.25) | 88.33 (7.39) | 25.39 (3.73) | 21.68 (3.45) |

*Figures in the parenthesis are standard deviation

The interaction effect of the grain variety and loading rate showed that the grains rupture force decreased from 79.60 to 73.66 of N and 67.68 to 55.01 N at loading rates of 5 and 10 mm/min, respectively, for Alikazemi and Hashemi varieties (Table 3). Mohsenin et al. (1963) found that the rate of deformation affected the maximum force that could be exerted by a steel plunger on apples. As the rate of deformation increased, the maximum force of rupture increased. Zoerb (1967) reported that most agricultural materials are elastic during the first portion of a load–deformation curve, but have viscoelastic properties with increased loading. Thus, once the elastic region is extended, properties are time-dependent and the effect of loading rate becomes more noticeable.

Table 3. Mean comparison of rupture force and energy of paddy grain considering interaction effect of variety and loading rate

| Variety | Rupture force (N) | | Rupture energy (mJ) | |
|---|---|---|---|---|
| | Loading rate | | | |
| | 5 mm/min | 10 mm/min | 5 mm/min | 10 mm/min |
| Alikazemi | 79.598 a* | 73.658 ab | 36.775 a | 30.697 b |
| Hashemi | 67.676 b | 55.006 c | 30.686 b | 25.252 c |

*The means with the same letter are not significantly different ($P > 0.05$) according to Duncan's multiple ranges test

The mean comparison of rupture force of paddy grain considering interaction effect of grain variety and grain orientation has given in Table 4. As shown, the required force to rupture the paddy grain decreases from 121.53 to 31.72 N and 99.15 to 23.54 N at horizontal and vertical orientations, respectively, for Alikazemi and Hashemi varieties. Based on the reports of Singh and Goswami (1998) in the case of cumin seed, the force required to initiate seed rupture decreased from 50 to 40 N and 31 to 20.3 N with an increase in moisture content from 7% to 13% d.b., for the horizontal and vertical orientations, respectively. Baritelle and Hyde (2000) determined strain rate and size effects on pear tissue failure. They showed that as the strain rate increased the failure stress also increased while failure strain remained nearly the same. Thus, toughness and stiffness of pear both increased with increasing strain rate.

The results indicating interaction effect of loading rate and grain orientation for the two evaluated varieties are given in Table 5. It can be seen from Table 5 that with increase in loading rate from 5 to 10 mm/min, rupture force decreases from 117.82 to 102.85 N and 29.45 to 25.81 N, at horizontal and vertical orientations, respectively. The effects of moisture content and grain orientation on the rupture force and the rupture deformation of the safflower hull was studied by Baumler et al. (2006), who reported that no important difference in rupture force between both seed orientations was measured. They suggested the force required for the hull rupture decreases as the moisture content increased, and it attained a minimum value at around 11% d.b., followed by an increasing trend with further increase in moisture content. Teotia et al. (1989) studied the force required to cause deformation and subsequent rupture in a pumpkin seed. It was reported that the hull breaking load varied from 30 to 50 N for dry seeds and from 14 to 36 N for wet seeds, following quasi-static compression with horizontal and vertical orientations of the seed.

Table 4. Mean comparison of rupture force and energy of paddy grain considering interaction effect of variety and grain orientation

| Variety | Rupture force (N) | | Rupture energy (mJ) | |
|---|---|---|---|---|
| | Grain orientation | | | |
| | Horizontal | Vertical | Horizontal | Vertical |
| Alikazemi | 121.531 a* | 31.725 c | 39.753 a | 27.719 c |
| Hashemi | 99.146 b | 23.536 c | 31.809 b | 24.129 c |

*The means with the same letter are not significantly different ($P > 0.05$) according to Duncan's multiple ranges test

Table 5. Mean comparison of rupture force and energy of paddy grain considering interaction effect of grain orientation and loading rate

| Grain orientation | Rupture force (N) | | Rupture energy (mJ) | |
|---|---|---|---|---|
| | Loading rate | | | |
| | 5 mm/min | 10 mm/min | 5 mm/min | 10 mm/min |
| Horizontal | 117.824 a* | 102.853 b | 38.546 a | 33.016 b |
| Vertical | 29.450 c | 25.811 c | 28.915 c | 22.933d |

*The means with the same letter are not significantly different ($P > 0.05$) according to Duncan's multiple ranges test

**3.2 Rupture Energy**

The mean comparison of the grains rupture at different varieties, grain orientations and loading rates is given in Table 6. As it can be seen, the energy absorbed by the paddy grain before initiating its rupture in the case of Hashemi variety was obtained lower than that of the Alikazemi variety, at similar conditions of the grain orientation and loading rate.

Table 6. Mean comparison of rupture energy of paddy grain at different varieties, grain orientations and loading rates

| | Rupture energy (mJ) | | Rupture energy (mJ) | |
|---|---|---|---|---|
| Grain Orientation | Horizontal | | Vertical | |
| | Loading rate | | | |
| Variety | 5 mm/min | 10 mm/min | 5 mm/min | 10 mm/min |
| Alikazemi | 42.70 (7.17) | 36.80 (6.24) | 30.85 (4.98) | 24.59 (3.21) |
| Hashemi | 34.39 (2.64) | 29.23 (1.60) | 26.98 (2.95) | 21.27 (2.73) |

*Figures in the parenthesis are standard deviation

The results also showed that the paddy grain is more flexible and is more resistant to rupturing in the horizontal direction of loading as compared to the vertical, for both the evaluated varieties. This is possibly due to the fact that under vertical loading, smaller contact area of the grain with the compressing plates results in the expansion of high stress in the paddy grain. Gupta and Das (2000) reported that the sunflower seeds loaded in a vertical orientation absorbed more energy (144.7–222.9 J/m$^3$) prior to rupture than those loaded in the horizontal

(95.21–84.2 J/m$^3$) orientation; while the sunflower kernels loaded in a vertical orientation required less energy (18.1–54.3 J/m$^3$) to rupture than those loaded in the horizontal (38.9–65.8 J/m$^3$) orientation. The results reported by Gupta and Das (2000) about the effect of orientation on the energy absorption in the case of sunflower kernels were consistent to the findings in the current research.

The interaction effect of variety and loading rate on the rupture energy of paddy grains is shown in Table 3. The results revealed that the rupture energy decreased from 36.77 to 30.69 mJ and 30.68 to 25.25 mJ, respectively for Alikazemi and Hashemi varieties, as the loading rate increased from 5 to 10 mm/min. Energy absorbed at grain rupture was a function of both force and deformation up to rupture point. At low loading rate, the grain requires high force to be ruptured and its deformation was low but at high loading rate, the rupture force was low and the deformation was high. These results showed that energy absorbed at grain rupture decreases as the loading rate increases indicating low resistance to grain rupture during compressive loading. This attribute may lead to increase the percentage of broken grains during dynamic projects. The mean comparison of paddy grains rupture energy considering the interaction effect of grain variety and grain orientation is shown in Table 4. As it can be seen, the absorbed energy by the paddy grain until occurrence grain rupture decreases from 39.75 to 27.72 mJ and 31.81 to 24.13 mJ at horizontal and vertical orientations, respectively, for Alikazemi and Hashemi varieties. The interaction effect of loading rate and grain orientation on grain rupture energy is shown in Table 5. The results presented in Table 5 show that with increase in loading rate from 5 to 10 mm/min, grain rupture energy decreases from 38.54 to 33.01 mJ and 28.91 to 22.93 mJ, at horizontal and vertical orientations, respectively. Although the obtained results in this research concerning the effect of grain orientation on paddy grain rupture force and energy were opposite to those reported by Singh and Goswami (1998) for cumin seed, similar trends were reported by Saiedirad et al. (2008) regarding the effect of loading rate and grain orientation on grain rupture force and energy in the case of cumin seeds. They studied Effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed under quasi-static loading. They determined the fracture resistance of the cumin seed for loading rates of 2 and 5 mm/min, and showed that both rupture force and energy decreased as loading rate increased. Their results showed that the force required for initiating seed rupture decreased from 47.62 to 43.11 N and 14.06 to 13.43 N, and the energy absorbed at seed rupture decreased from 12.52 to 11.48 mJ and 4.96 to 4.26 mJ, with increase in loading rate from 2 to 5 mm/min, for horizontal and vertical orientations, respectively.

Agricultural materials and food products deform in response to the applied forces. The nature of the response varies widely among different materials. The amount of force and energy required to produce a given amount of deformation can be used to study the damage which occurs during harvesting and handling of grains and seeds. Such information often gives insight into the specific circumstances that lead to failure (i.e. cracking or splitting) and how such a failure can be prevented (Stroshine and Hamann, 1994).

## 4. Conclusions

The values of rupture force and rupture energy of paddy grains in the case of Alikazemi variety was obtained higher than those of Hashemi variety. So, it can be concluded that the Alikazemi variety is more resistant to breakage than the Hashemi variety during the grains processing operations such as de-husking, milling and polishing. The results revealed that paddy grains are more flexible in the horizontal loading direction and the rupture under vertical loading demanding less energy than under horizontal loading. This is may be due to decreasing contact area of the grains with loading plate and probably the occurring buckling phenomenon. As the rate of compressive loading increased from 5 to 10 mm/min, the grains rupture force and rupture energy decreased, for both the evaluated varieties. Based on this result, for processing paddy grains, lower rates of compressive loadings are recommended to minimize the percentage of damaged grains.

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